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Modulation of corticospinal output during goal-directed actions: Evidence for a contingent coding hypothesis

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ABSTRACT

Seeing a person perform an action activates the observer's motor system. The present study aimed at investigating the temporal relationship between execution and observation of goal-directed actions. One possibility is that the corticospinal excitability (CSE) follows the dynamic evolution of the pattern of muscle activity in the executed action. Alternatively, CSE may anticipate the future course of the observed action, prospectively extrapolating future states. Our study was designed to test these alternative hypotheses by directly comparing the time course of muscle recruitment during the execution and observation of reach-to-grasp movements. We found that the time course of CSE during action observation followed the time course of the EMG signal during action execution. This contingent coding was observed despite the outcome of the observed motor act being predictable from the earliest phases of the movement. These findings challenge the view that CSE serves to predict the target of an observed action.

1. Introduction

Observing other people's actions is associated with changes in the corticospinal projections of muscles that would be engaged in replication of the action being observed (Fadiga et al., 2005, 1995). These changes are commonly interpreted as evidence of *covert motor simulation* of the observed action (Fadiga et al., 1995), however, the precise computation reflected in corticospinal excitability (CSE) – what is precisely simulated – remains a source of ongoing research and debate (Naish et al., 2014).

An open question is whether during the observation of *goal-directed actions,* CSE is modulated to reflect future motor outcomes (Cavallo et al., 2013, 2012; Mc Cabe et al., 2015). Goal-directed actions such as prehension are, by definition, conceived and shaped in anticipation of future states (Grafton, 2010; Hommel, 2003). For example, when reaching toward and grasping an object, kinematic parameters such as wrist velocity and grip aperture already specify object size at 10% of movement duration (Ansuini et al., 2015). What is more, human observers are sensitive to the prospective information conveyed by movement kinematics and can use this information to anticipate the target of an observed action. As early as 80 ms after movement onset, for example, they are able to discriminate the size of an occluded target, i.e., whether the target is small or large (Ansuini et al., 2016).

Does CSE follow the same anticipatory course during observation of goal-directed actions?

If observers covertly simulate the future of the observed action with their motor system, one would expect that CSE runs ahead of execution, reflecting an extrapolation of the forthcoming EMG pattern beyond the action phase actually perceived. We refer to this as the *prospective coding* hypothesis. Indirect support for this hypothesis comes from the finding that observing snapshots of the start and the middle postures of grasp actions engenders a significantly higher CSE than observing their final postures (Urgesi et al., 2010). This has been interpreted to suggest that CSE is involved in the anticipatory simulation of observed actions, thus playing a functional role in action understanding.

However, observing a posture as an isolated snapshot or in the context of a movement may not recruit the same neural processes. Another possibility, thus, is that despite the availability of prospective kinematic information to predict the target of the observed action, CSE follows the dynamic evolution of the pattern of muscle activity in the executed action. In line with earlier studies showing a tight coupling between movement execution and observation (Borroni et al., 2008, 2005; Montagna et al., 2005), this would support a *contingent coding* hypothesis of goal-directed movements, that is, the observation

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dynamics is contingent upon execution dynamics.

To test these alternative hypotheses, in the current study we first acquired kinematic and electromyographic (EMG) data while participants performed reach-to-grasp actions toward a large and heavy object (grapefruit) and a small and light object (hazelnut; Study 1). Next, using transcranial magnetic stimulation (TMS) in conjunction with EMG, we probed the time course of motor evoked potentials (MEPs) recorded in the same hand muscles over the viewing of the same actions (Study 2). We used the intrinsic differences in the time course of kinematic and EMG activity observed in Study 1 to make inferences about the potential sources of MEP modulation observed in Study 2. If CSE projects the probable future course of the action, then MEPs should specify the intrinsic properties of the object to be grasped as soon as prospective kinematic information is available in the observed action. This is well before activity in the recorded hand muscles differentiates the two objects during action execution. By contrast, if motor simulation contingently follows action execution, then despite the availability of kinematic information to predict the target of the observed action, the time course of MEP modulation should follow the course of EMG during execution.

2. Study 1: action execution

Study 1 was designed to characterize the temporal profile of kinematic and EMG activity associated with the execution of reach-to-grasp movements performed toward small and light objects versus large and heavy objects.

2.1. Methods

2.1.1. Participants

Fifteen volunteers (8 females; mean age 28 years; age range 23–35) participated in the study. All participants had normal or corrected-to-normal vision and had no history of neurological or psychological disorders. They all self-reported to be right-handed. Written informed consent was obtained from each participant. The study was approved by a local ethics committee (ASL 3 Genovese) and was carried out in accordance with the principles of the revised Helsinki Declaration (World Medical Association General Assembly, 2008).

2.1.2. Stimuli and apparatus

The to-be-grasped object was either a grapefruit (diameter = about 10 cm; weight = about 354 g; now on referred to as the "large object") or a hazelnut (diameter = about 1.5 cm; weight = about 2 g; now on referred to as the "small object"). The working space was set on the surface of a table (width = 140 cm; length = 70 cm) covered with a black cloth. A motion capture system (Vicon System) consisting of eight near-infrared cameras was used to track the 3D coordinates of 20 lightweight retro-reflective markers (4 mm in diameter) placed on the radial aspect of the wrist, the metacarpophalangeal joint and tip of the index finger, the metacarpophalangeal joint of the little finger, and the trapezium bone and tip of the thumb. Hand kinematics were collected at 100 Hz and then low-pass filtered using a fourth-order Butterworth filter and a cut-off frequency of 6 Hz.

Surface EMG measurements were used to estimate the influence of object properties on muscle activation. Surface electrodes (9 mm in diameter) were placed using a belly–tendon mount over two intrinsic hand muscles: the first dorsal interosseous (FDI) and the abductor digiti minimi (ADM) muscles of the right hand. Ground electrodes were placed on the wrist.

In addition, movements were also video-recorded for presentation in the action observation experiment (Study 2). Recordings were made from the lateral viewpoint using a digital video camera (Sony Handycam 3-D) placed about 120 cm from the hand start position. Video camera position and arrangement were kept constant for the entire duration of the study. The hand was in full view from the beginning until the end of the movement.

2.1.3. Procedure

Participants were seated on a height-adjustable chair with the elbow and wrist resting on a table, the forearm pronated, the right arm oriented in the parasagittal plane passing through the shoulder, and the right hand in a semi-pronated position, with the tips of the thumb and index finger on a tape-marked point. The angular position of the wrist was also controlled in order to guarantee consistency of the starting position across participants. Participants were asked to reach for, grasp and move the object to an area located 50 cm to the left of the object's initial position. Depending on the condition, either the large or the small object was placed on the table. The object, positioned at a distance of about 48 cm from the starting position, was aligned with the participant's midline. The angle between the sagittal plane passing through the object and the hand start position was about 35°. Participants were asked to grasp the objects at a natural speed using their right hand. The experimenter visually monitored the performance in each trial to ensure the participants' compliance with these requirements. Each subject performed a total of 60 trials in 6 separate blocks of 10 trials (3 blocks of 10 trials for each of the 2 sizes of object). Blocks were presented in a ABAB design to ensure that participants were not asked to perform the same movement more than ten times in a row. The order of the blocks was counterbalanced across participants. The experimental session was preceded by a practice session to familiarize participants with the task (20 practice trials: 10 small object trials, 10 large object trials).

2.1.4. Data analysis

2.1.4.1. Kinematic data. The analysis of kinematic data, as well as detailed kinematic results are published in Ansuini et al. (2015) and partially reported in Ansuini et al. (2016). In the following, we provide a brief summary of the analysis relevant to the present study. Custom software (Matlab; MathWorks, Natick, MA) was used to compute the following kinematic variables:

- *wrist velocity:* defined as the module of the velocity of the wrist marker (mm/sec);
- *wrist height:* defined as the z-component of the wrist marker (mm);
- *grip aperture:* defined as the distance between the marker placed on thumb tip and that which was placed on the tip of the index finger (mm).

These variables were expressed with respect to the original frame of reference (i.e. the frame of reference of the motion capture system, termed as the global frame of reference; F_{global}). Furthermore, to provide a better characterization of the hand joint movements, we also analyzed kinematic parameters expressed with respect to a local frame of reference centred on the hand (i.e. F_{local}) (for a similar method see Carpinella et al., 2006; Carpinella et al., 2011). Within F_{local}, we computed the following variables:

- *x-*, *y-* and *z-thumb*: defined as x-, y- and z-coordinates for the thumb with respect to F_{local}(mm);
- *x-*, *y-* and *z-index*: defined as x-, y- and z-coordinates for the index with respect to F_{local}(mm);
- *x-*, *y-* and *z-finger plane*: defined as x-, y- and z-components of the thumb-index plane, i.e. the three-dimensional components of the vector that is orthogonal to the plane. This variable provides information about the abduction/adduction movement of the thumb and index finger, irrespective of the effects of wrist rotation and finger flexion/extension.

All variables were calculated by only considering the reach-to-grasp phase of the movement, i.e. from reach onset (the time at which the

wrist velocity first crossed a 20 mm/s threshold) to grasp offset (the time at which the wrist velocity dropped below a 20 mm/s threshold). Each of the 12 variables was expressed with respect to normalized (%) rather than absolute (ms) duration, and was then resampled at intervals of 10% of the normalized movement time (from 10% to 100%), rather than absolute movement durations (small object mean ± SEM = 780 ± 16 ms; large object mean ± SEM = 745 ± 20 ms). A classification analysis based on a Gaussian Kernel Support Vector Machine algorithm (SVM; Cortes and Vapnik, 1995) was used to determine the extent to which hand kinematics specified object intrinsic properties. Accuracy rates were computed from a ten-fold cross validation scheme in which values were averaged.

In addition, to evaluate the importance of each kinematic feature in the classification of the object properties, we used the F-score criterion (Yang et al., 2014). F-score is a simplified Fisher criterion (Duda et al., 2000), which is suitable to estimate the discriminative power of single features as well as of group of features (feature vectors). All kinematic features of each class composed the feature vector "F-group score".

2.1.4.2. EMG data. Differently from kinematic data, EMG data and results have not been published in previous studies. EMG data were acquired as analog signals synchronized to the motion capture Vicon system through a MX Giganet. Data were acquired at a sampling rate of 1 kHz and band-pass filtered at 10–250 Hz. As for kinematic data, EMG data were analyzed by only considering the reach-to-grasp phase of the movement. For off-line analysis, EMG data were then rectified and filtered with a low-pass filter of 8 Hz. Within each participant, for each muscle the rectified data were resampled and averaged in epochs of 10% of the normalized movement time to obtain ten time bins (i.e., 10%, 20%, 30% until 100% of movement time). To confirm the presence of a muscle-specific contribution to grasping a small object as compared to a large object, for each muscle and time bin, we divided the mean EMG activity during the grasping of the large object by the mean EMG activity during the grasping of the small object. The resulting "EMG ratio" provides an index of EMG object specification, that is, the relative degree to which, for each time bin, the EMG activity is greater for a large as compared to a small object. An index higher than 1 indicates greater

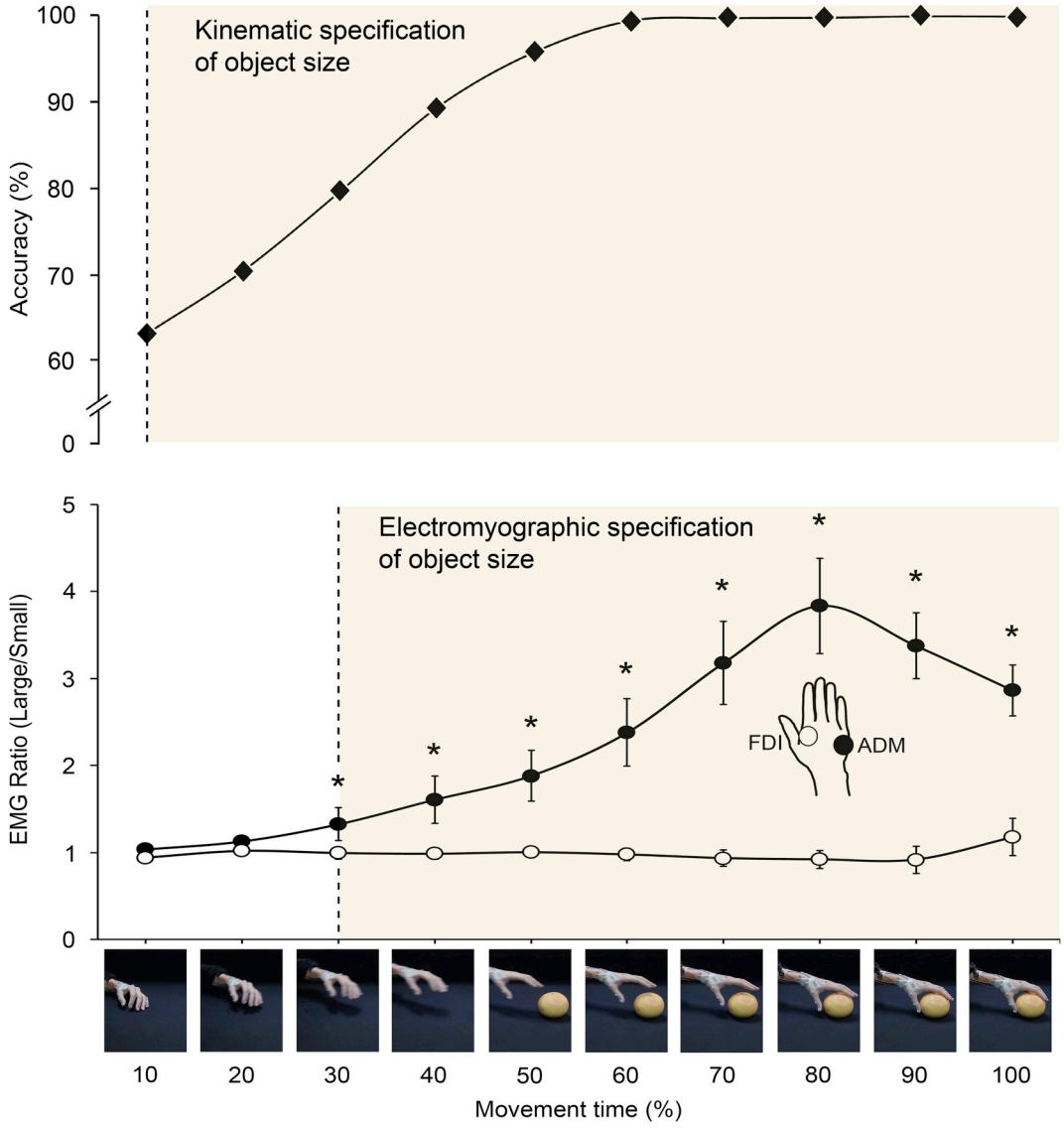

Fig. 1. Action execution results. (Upper panel) Temporal evolution of the classification accuracy using kinematic variables as predictive features for the classification algorithm. SVM classification results have been previously published in Ansuini et al. (2015) and Ansuini et al. (2016). (Lower panel) Modulation of EMG activity over time (from 10% to 100% of the movement duration, in 10 steps). EMG ratios were calculated for the FDI (open circles) and the ADM (filled circles) as mean EMG activity during the grasping of the large object divided by mean EMG activity during the grasping of the small object. Bars indicate Standard Error. Asterisks (*) denote significant pairwise comparisons ($p < .05$). The shaded area demarks the time at which object size-related modulation starts to be significant.

EMG activity for large compared to small objects, while an index lower than 1 indicates greater EMG activity for small compared to large objects. An index of 1 indicates no object-related modulation. To evaluate the influence of time on the considered muscles, EMG ratios were submitted to a repeated measures ANOVA with Muscle (FDI, ADM) and Time (10 levels; from 10% to 100% of movement duration) as within-subjects factors. For post hoc comparisons, multiple pairwise tests were conducted, applying the Bonferroni correction (alpha level = .05).

2.2. Results

As previously reported in Ansuini et al. (2015) and Ansuini et al. (2016), results of classification analysis of the kinematic data revealed that already at 10% and 20% of the movement duration, kinematic features predicted, with above chance accuracy, the intrinsic properties of the object to be grasped (63.15% and 70.47%, respectively). Classification accuracy increased rapidly as time progressed, exceeding 95% of accuracy at 50% of movement duration (95.81% at 50%, 99.48% at 60%, and 99.97% at 100% of movement duration) (Fig. 1, upper panel). Similarly, we found that F-scores increased across time intervals (F scores of each kinematic variable are depicted in Supplementary Fig. 1).

ADM EMG ratios were significantly greater than 1 from 40% to 100% of movement time (one tailed p-values ranging from <0.001 to 0.021). In contrast, FDI EMG ratios were close to 1 for the entire movement duration (one tailed p-values ranging from 0.076 to 0.497). The ANOVA conducted on EMG ratios revealed a main effect of Muscle ($F_{(1,14)} = 27.552$; $p < .001$; $\eta^2_p = .663$) and Time ($F_{(9,126)} = 14.236$; $p < .001$; $\eta^2_p = .504$). These effects were further qualified by a significant Muscle by Time linear interaction ($F_{(1,14)} = 42.498$; $p < .001$; $\eta^2_p = .752$), reflecting the linear increment in ADM ratio but not in FDI. Post hoc comparisons showed that EMG ratios were significantly larger in the ADM when compared to the FDI, from 30% of movement duration to the time of contact (all p-values < .05 from 30% to 100% of movement duration). No modulation related to the intrinsic properties of the object was observed in the EMG signal from 10% to 20% of movement duration (Fig. 1, lower panel).

3. Study 2: action observation

Study 2 was designed to assess the time course of CSE during *observation* of the reach-to-grasp movements. Based on the results of Study 1, we chose three time points to characterize MEP modulation: 20%, 50% and 80% of movement duration. If CSE anticipates the predicted course of the action, we would expect that MEPs specify object intrinsic properties at 20% of movement duration; that is, as soon as kinematic input is available to predict the target of the action. Alternatively, if CSE follows the dynamics of the EMG signal, we would expect an increase of the MEP amplitudes over time, with the earliest size-related difference in MEPs in correspondence or after the first significant difference in the EMG signal (that is, from 50% of movement duration).

3.1. Methods

3.1.1. Participants

A new group of twenty volunteers (10 females; mean age 22 years; age range 19–26) was recruited for Study 2. None of the participants of this study had taken part in the action observation study reported by Ansuini et al. (2016). We based our sample size on previously published studies testing CSE during observation of visual stimuli (Borgomaneri et al., 2015; Bunday et al., 2016; Cardellicchio et al., 2013). All participants self-reported to be right-handed, had normal or corrected-to-normal visual acuity and were free from any contraindications to TMS (Rossi et al., 2009). Before the experiment took place, the participants – who were naïve as to the purposes of the study – gave their written informed consent. The experimental procedures were approved by a local ethical committee (Comitato di Bioetica di Ateneo, University of Turin) and were carried out in accordance with the principles of the revised Helsinki Declaration (World Medical Association General Assembly, 2008). Participants were financially compensated for their time. None of them reported experiencing discomfort or adverse effects during TMS.

3.1.2. Materials

3.1.2.1. Movement selection. Movements to be included in the action observation phase were selected in order to capture the relationship between EMG activity and object intrinsic properties over time. With this in mind, using the EMG data from Study 1, we first calculated the grand average of EMG activity separately for movements toward the small object and the large object (please refer to Ansuini et al., 2016 for a similar procedure). Then, for each object, we computed the Euclidian distance between the muscle activity in each trial of all participants and the grand average. Next, we selected the 20 movements that, for each object, minimized this distance. This procedure allowed us to identify a subset of movements that were representative of the two objects.

3.1.2.2. Stimuli. Forty unique video clips (hereafter referred to as "*grasp*" videos) corresponding to the selected movements (20 small object, 20 large object) were edited using Adobe Premiere Pro CS6 (.avi format, disabled audio, 25 frames/s). Grasp videos showed the right arm, forearm and hand of the agent from a lateral viewpoint. Duration of videos varied according to the actual duration of movements and did not differ between the two conditions (small object mean ± SEM = 776.00 ± 19.55; large object mean ± SEM = 730 ± 19.65; $t_{38} = 1.659$, $p = .105$).

Each video was edited to spatially occlude the to-be-grasped object. The spatial occlusion was obtained by superimposing a black mask (i.e., a semicircular disk) on the target object location. The size and the position of this mask were kept constant across participants. Additionally, grasp videos were temporally occluded at three time points: 20%, 50% and 80% of movement duration (see Supplementary Videos 1–6). A set of videos displaying a sequence of horizontally oriented white squares illuminated in succession by turning orange (hereafter referred to as "*square*" videos) were used as control stimuli. To match the occlusion times for grasp videos, square videos showed the illumination of 2, 5 or 8 squares, such that the duration of the square videos displaying two illuminated squares equaled the average duration of the grasp videos occluded at 20% of movement time, and so on.

Supplementary video related to this article can be found at doi:10.1016/j.neuropsychologia.2019.107205

3.1.3. Electromyographic and TMS recording

CSE was assessed based on the amplitude of MEPs recorded simultaneously from the right FDI and ADM by means of a Biopac MP-150 (Biopac Systems, Inc., Santa Barbara, CA). EMG signals were sampled at 5000 Hz, amplified at a gain of 2000, band-pass filtered (10–500 Hz) and stored for off-line analysis. Pairs of Ag–AgCl surface electrodes were placed over the muscle belly (active electrode) and over the associated joint or tendon (reference electrode). The ground was placed over the participant's right wrist.

TMS pulses were administered via a Magstim Rapid2 stimulator (Magstim, Dyfed, UK) connected to a 70 mm figure-of-eight coil positioned over the left primary motor cortex (M1) hand region. The coil was held tangentially to the scalp with the handle pointing backward and laterally at 45° to the midline; this orientation was chosen on the basis of the evidence that the lowest motor threshold is achieved when the induced electric current in the brain flows approximately perpendicular to the central sulcus (Brasil-Neto et al., 1992; Mills et al., 1992). The coil was positioned at the optimal scalp position (OSP), defined as the position that could produce reliable MEPs simultaneously from the FDI and the ADM (i.e. the same muscles in the execution experiment). To find the

individual OSP, the coil was moved in 1-cm steps over the motor cortex; once found, the OSP was marked on a bathing cap, worn by the participant, thereby ensuring correct coil placement throughout the experiment. Then, the individual resting motor threshold (rMT) was determined through an adaptive parameter estimation by sequential testing procedure (PEST) with the Motor Threshold Assessment Tool 2.0 (Mishory et al., 2004). Mean rMT was 62.6% (SEM = 2.49) of the maximum stimulator intensity. During the experimental session, stimulation intensity was set at 110% of rMT (Di Lazzaro et al., 2004; Loporto et al., 2013). EMG data were collected from 100 ms before to 200 ms after the TMS pulse.

3.1.4. Procedure

The experiment was carried out in a dimly lit room. Participants sat in a comfortable armchair in front of a 24-in. monitor (resolution 1280 x 800 pixels, refresh frequency 75 Hz, viewing distance 70 cm) on which the video clips were displayed. Each *grasp* trial began with the appearance of a fixation cross for 3000 ms, followed by the presentation of a video clip displaying a reach-to-grasp movement occluded at 20, 50 or 80% of movement duration. A single TMS pulse was administered in 67% of the trials (120 trials, 20 per occlusion time for each object size); no pulse was administered in the remaining 33% of the trials (60 trials). Based on previous evidence showing that processing time associated with evoked change in CSE during action observation likely requires between 40 and 80 ms (Gueugneau et al., 2015), TMS pulses were synchronized to the offset of the last video frame for each of the three temporal occlusions (each frame lasting 40 ms). On non-TMS trials, after the presentation of the video clip participants were asked to judge the size of the to-be-grasped object. Task structure conformed to a one-interval forced choice task in which a grasp toward either a small or a large object was displayed. Participants were asked to report whether the occluded to-be-grasped object was large or small by pressing, with their left hand, one of two keys on a wireless mouse, one key to indicate "small", and the other key to indicate "large". The question "Was the movement directed toward a large or small object?" (in Italian) appeared in written form after each video. Participants had a maximum time of 5000 ms to respond. After this time had elapsed, they were asked to verbally rate the confidence in their decision on a four-point scale (from 1 = least confident, to 4 = most confident).

To rule out unspecific effects related to stimulus duration, participants completed 72 *square* trials displaying 2, 5 or 8 illuminated squares that were randomly interspersed within the experimental session. A single TMS pulse was administered at the end of the video in 60 trials (20 per condition). In the remaining 12 trials, no pulse was administered and, after the video, a question appeared on the screen, asking participants to verbally report the number of illuminated squares. To avoid cumulative effects of TMS (Chen et al., 1997), the rest period between trials was at least 8 s. We also recorded two series of 10 MEPs, before and after the experimental session, while participants watched *square* videos displaying 8 squares that were illuminated in succession. A single TMS pulse was administered at the end of each video clip. Comparisons of MEP amplitudes in these two series allowed us to check for any corticospinal excitability change related to TMS per se. Thus, participants completed a total of 252 trials, divided into 4 blocks of 63 trials, with each block lasting approximately 12 min. Stimulus presentation timing, EMG recording and TMS triggering, as well as randomization of stimuli were controlled by using the E-Prime V2.0 software (Psychology Software Tools, Pittsburgh, PA). A single experimental session lasted approximately 60 min.

3.1.5. Data analysis

We used the participants' responses and confidence ratings to estimate signal detection theory (SDT) parameters. The proportion of hits (arbitrarily defined as small object responses when the target was the small object) and false alarms (arbitrarily defined as small object responses when the target was the large object) was calculated for each participant for each temporal occlusion and combined with their confidence ratings to determine points on an empirical receiver operating characteristic (ROC) curve. Because each response had four associated ratings, there were eight possible responses for each trial (from highest confidence in one alternative to highest confidence in the other), resulting in seven points on the ROC curve. Then, for each participant and each temporal occlusion, we plotted the points on the ROC curve to determine the area under the curve (AUC). The AUC is a measure of sensitivity unaffected by response bias and can be interpreted as the proportion of times that the participants would correctly identify the target, if the target and non-target were presented simultaneously (for a similar approach see Azzopardi and Cowey, 1997; Ricci and Chatterjee, 2004; Tamietto et al., 2015; Van den Stock et al., 2014). A diagonal ROC curve, which coincides with an AUC of 0.5, shows a chance level classification score. This curve would be interpreted as the observer having a 50% probability of correctly discerning between movements toward small and large objects. By contrast, an ROC curve on the left upper bound of the diagonal encompassing the entire unit square (so that the AUC is 1), indicates a perfect positive prediction with no false positives and an optimal decoding score. This curve would be interpreted as the observer having a 100% probability of correctly discerning between movements toward small and large objects.

Neurophysiological data were analyzed off-line using custom written Matlab script (MathWorks, Natick, MA) and SPSS Statistics V.23.0 Software (SPSS INC., Chicago, IL, USA). In order to prevent contamination of the MEP measurements by background EMG activity, trials with peak-to-peak activity greater than 100 μV in the 100 ms window preceding the TMS pulse were excluded from the MEP analysis (4%). Peak-to-peak MEP amplitude was calculated for each muscle for each trial. MEP amplitudes of less than 50 μV (7%) or deviating more than 2.5 standard deviations (SDs) from the mean of each muscle in each experimental condition (9%) were excluded as outliers. For *'grasp'* trials, MEPs showed an evident positive skew, as confirmed by the Shapiro-Wilk test (W_s ranging from = 0.831 to 0.896, $p_s < .05$). To address the non-normality of data distribution, for each muscle and each stimulation point, we divided the mean MEP size recorded during the observation of movements toward the large object by the mean MEP size recorded during the observation of movements toward the small object. The resulting MEP size ratio indicates the relative degree to which the MEPs are greater for large compared to small objects. Specifically, an index higher than 1 indicates larger MEPs for large compared to small objects, while an index lower than 1 indicates larger MEPs for small compared to large objects. An index of 1 indicates no object-related modulation. Using a similar logic, for *'square'* trials, for each muscle and each stimulation point, the mean MEP size was divided by the MEPs average size obtained in the two series of 10 MEPs collected before and after the experimental session.

MEP ratios for '*grasp*' trials and '*square*' trials were then submitted to two separate repeated measures ANOVAs with Muscle (FDI, ADM) and Time (20%, 50% and 80%) as within-subjects factors. For post hoc comparisons, multiple pairwise tests were conducted, applying the Bonferroni correction (alpha level = .05). Neither behavioral nor MEP results have been published in any previous work.

3.2. Results

Data from three participants were excluded from the analysis because of MEP amplitudes deviating more than 2 SD from the group average in all conditions. Thus, the final sample included 17 participants (8 females; mean age 22 years; age range 19–26).

AUC values increased across progressive occlusions (20% of movement duration: M = 0.804, SEM = 0.020; 50% of movement duration: M = 0.995, SEM = 0.004), reaching a perfect discrimination performance at 80% of movement duration (M = 1, SEM = 0). One-sample t-tests revealed that already at 20% of movement duration, AUC values exceeded the chance level of 0.5 ($t_{16} = 15.504$; $p < .001$; 95% CI [0.262,

0.345]; 50% of movement duration: $t_{16} = 140.590$; $p < .001$; 95% CI [0.488, 0.503]) (Fig. 2A). This indicates that participants were able to predict object size from the earliest phases of the movement.

A comparison of mean raw MEP amplitudes recorded pre- and post-session revealed no significant difference in either of the two muscles (FDI: $t_{16} = 1.492$; $p = .155$; ADM: $t_{16} = 0.206$; $p = .840$). For *grasp* trials, ADM MEP ratios where higher than 1 at 80% of movement time (one tailed $p = .034$). In contrast, FDI MEP ratios did not differ from 1 at any time point (one tailed p-values ranging from 0.171 to 0.271). The ANOVA conducted on MEP ratios showed no main effect of Muscle ($F_{(1,16)} = 2.633$; $p = .124$; $\eta^2_p = .141$) and no main effect of Time ($F_{(2,32)} = 0.745$; $p = .483$; $\eta^2_p = .044$). There was, however, a significant linear interaction between Muscle and Time ($F_{(1,16)} = 12.850$; $p = .002$; $\eta^2_p = .445$), reflecting the fact that the difference in MEP ratios between the two muscles increased linearly over time. Post hoc comparisons showed that at 80% of movement duration, MEP ratios were significantly greater for the ADM as compared to the FDI ($p = .005$). No other comparison approached significance ($0.239 < p > .390$) (Fig. 2B).

For *square* trials, neither the main effect of Muscle ($F_{(1,16)} = 0.579$; $p = .458$; $\eta^2_p = .035$; FDI: $M = 1.504$, $SEM = 0.244$; ADM: $M = 1.330$, $SEM = 0.137$) nor the main effect of Time ($F_{(2,32)} = 0.975$; $p = .388$; $\eta^2_p = .057$; 20% of movement duration: $M = 1.348$, $SEM = 0.154$; 50% of movement duration: $M = 1.448$, $SEM = 0.176$; 80% of movement duration: $M = 1.455$, $SEM = 0.176$) approached significance. The interaction Muscle by Time ($F_{(2,32)} = 1.342$; $p = .276$; $\eta^2_p = .077$) was also not significant. This finding rules out the possibility that MEP modulation unspecifically reflected stimulus duration.

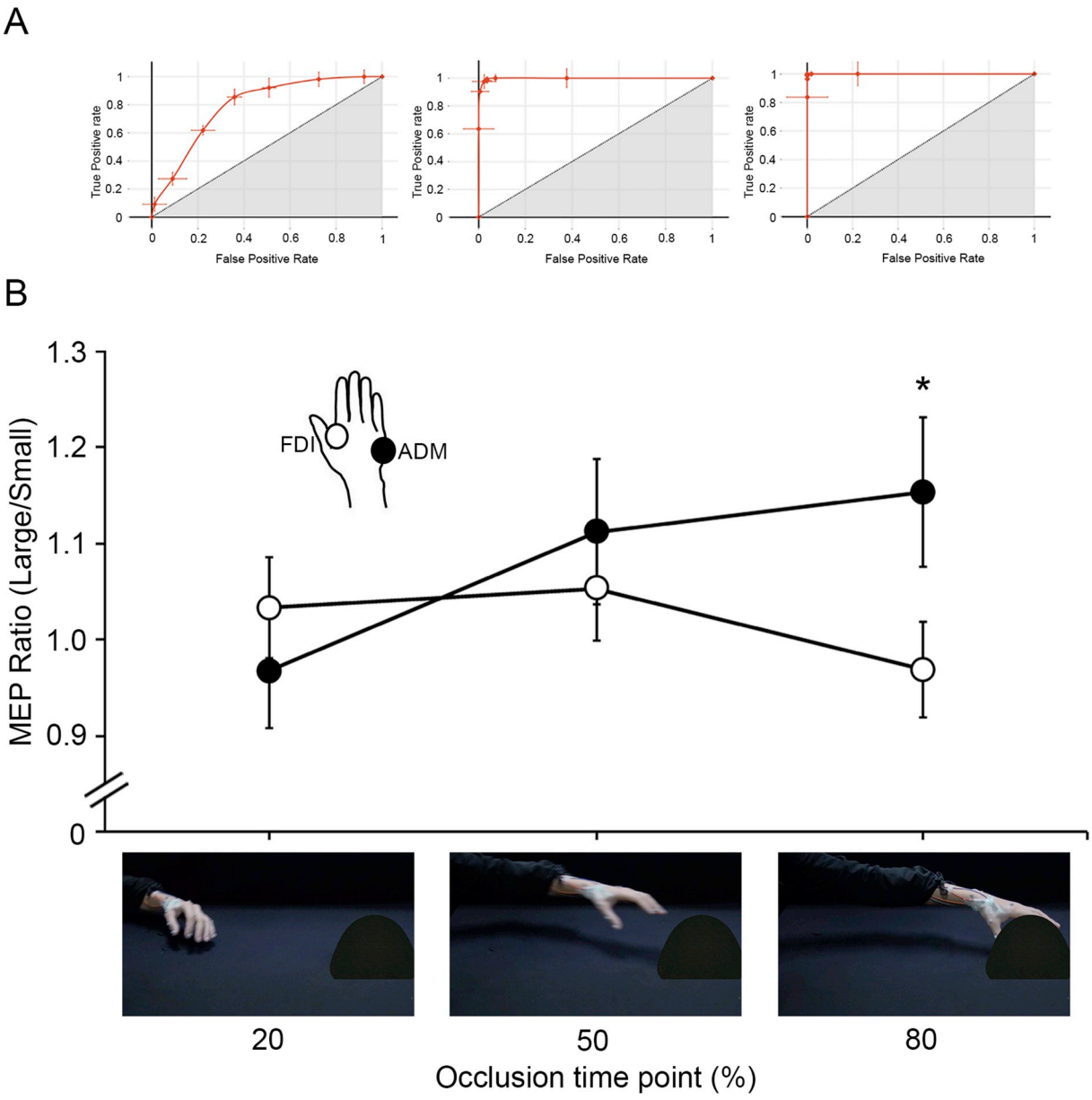

Fig. 2. Action observation results. (A) The 7-point ROC curves derived from the participants' ratings show the probability of a true positive rate (hit) versus a false positive rate (false alarm) for reach-to-grasp movements toward small and large objects as a function of the occlusion time point (20%, 50% and 80% of the movement duration). The discrimination ability increases as the ROC curve moves from the diagonal (dashed line corresponding to 0.5 random guess performance) toward the upper left boundary of the graph (1.0 perfect performance). (B) Modulation of MEP ratios at three occlusion time points for the FDI (open circles) and the ADM (filled circles). MEP ratios were calculated as mean MEP size during the observation of movements toward the large object divided by mean MEP size during the observation of movements toward the small object. Bars indicate Standard Error. Asterisk (*) denotes significant pairwise comparison ($p < .05$).

4. General discussion

Seeing a person perform an action activates the observer's motor system. The present study aimed at investigating the timing of CSE during observation of goal-directed actions. What is the relationship between the time course of muscle activation during observation and execution of goal-directed actions? Does CSE anticipate the future course of the observed action, prospectively extrapolating the predicted action goal? Or does it rather follow the pattern of muscle activity in the executed action? We tested the respective predictions of these two alternative hypotheses.

We found at the behavioral level, in line with Ansuini et al. (2016), that participants were able to predict the object size of an observed reach-to-grasp action already at 20% of movement duration. In contrast, the pattern of corticospinal modulation did not reach significance until 80% of movement duration, showing an increase over the three selected time points (20%, 50%, and 80% of movement durations). This pattern of results is difficult to reconcile with the hypothesis of a prospective extrapolation of future states, functionally contributing to action prediction. However, this finding is compatible with the hypothesis of a contingent coding of the observed grasp.

But how tight is the coupling between execution and observation? The contingency coding hypothesis might take two versions. A *stronger* version of contingency hypothesis might predict that the time course of MEP modulation during action observation parallels the course of EMG during execution. This account would suggest a point-to-point correspondence between muscle recruitment during action execution and observation. A *weaker* version of the contingency hypothesis might suggest that muscle recruitment during action observation follows a course that is similar to action execution, but without precise mapping of the dynamic evolution of the EMG pattern (see Hamilton et al., 2007). This account would predict some degree of similarity but no exact correspondence between action execution and observation. In the current study, we observed significant object-related differences at 50% of movement duration during action execution, but not during action observation. These results appear in general agreement with the weaker version of the contingency hypothesis, but they do not fully support the stronger hypothesis about contingent coding. One limitation of the current study is the relatively low number of time-points in the action observation experiment. Further work, where more time points are mapped, is required to establish the exact nature of the contingency between execution and observation. A crucial step will involve increasing the sampling rate used to record CSE (by applying additional TMS pulses) to determine the precise temporal profile of CSE during action observation and capture the exact moment at which ADM and FDI MEP ratios start to diverge. A second limitation is inherent to TMS single pulse paradigms. EMG signal in the domain of action execution and MEPs in the domain of action observation are not statistically comparable. Thus, the conclusion that CSE during action observation contingently follows the EMG activity in action execution can only be inferential.

4.1. Contingent coding of predictable movements

A number of TMS studies carried out in the last years probed CSE modulation by introducing unexpected changes in movement kinematics (Cavallo et al., 2013; Gangitano et al., 2004; Gueugneau et al., 2015; Janssen et al., 2015). A common finding is that CSE modulation progresses first in accordance with the action that is anticipated, and, *if discrepancies are revealed*, coincides thereafter with the action that is observed (Gangitano et al., 2004).

Our results go beyond this indicating that even *when no discrepancies are revealed* and even *when the course of the observed action is fully predictable,* CSE follows the EMG pattern of the executed movements. We can therefore conclude that contingent coding within M1 does not arise from the unpredictability of the observed motor pattern, and that predictable motor patterns are likewise contingently followed over time. This raises a question about the function of contingent coding: why would CSE contingently map a motor act whose outcome is already predictable at 20% of movement duration?

One possibility, compatible with associative accounts of mirror neurons (Cook et al., 2014), is that CSE is driven by action-perception contingency learning. According to this hypothesis, CSE would have no specific function, only existing as by-product of learned associations between observed and executed actions.

Alternatively, modulations in CSE during action observation might reflect *hypothesis testing* (Donnarumma et al., 2017). According to this hypothesis, the most probable target would be estimated from advanced kinematic information gleaned from the earliest phase of the observed movement (Ansuini et al., 2016). Once the most probable target is estimated, the motor command to grasp the object is generated and fed into an internal model, or 'emulator', to track the movement that is actually executed in real-time. By comparing the predicted grasp with the actual grasp, the system is able to assess the likelihood of the initial prediction and evaluate the mechanical events that arise from interactions between the actor's hand and the object. On this account, the function of contingent mapping would be to calibrate the performance of the actor, rather than predict the target of the action (Kilner, 2011; Kilner et al., 2007). One way to assess this possibility would be to quantify the effects of CSE suppression on hypothesis testing. Palmer et al. (2016) found that suppression of motor excitability in M1 causes a reduction in an individual's sensitivity to interpret the kinematics of observed action. A functional role of CSE in hypothesis testing would predict a specific decrease in the ability to compare the predicted and actual sensory events following the suppression of activity in M1.

4.2. Contribution of other cortical areas

Another important aspect that still needs to be considered is the contribution of other cortical areas to the modulation of CSE. Evidence that other cortical areas influence the CSE modulation was first provided by Avenanti et al. (2007). By combining low-frequency repetitive and single-pulse TMS, they found that virtual lesion of the ventral premotor cortex (PMv) suppressed CSE facilitation contingent upon observation of possible and impossible movements. PMv-M1 interactions during action observation have also been reported using paired-pulse (dual-site) TMS. Using this paired-pulse TMS paradigm, Lago et al. (2010) showed that the M1 excitability increased in parallel with PMv-M1 connectivity when observing a hand grasping a ball. In contrast, observing a hand grasping a noxious object (e.g., a hot soldering iron) triggered a decrease in the strength of the PMv-M1 connectivity. Similarly, Koch et al. (2010) found that PMv-M1 connectivity was modulated when watching actions in which grasping posture was congruent with the goal of the action, but not when watching actions in which grasping posture was incongruent. Anterior Intraparietal Sulcus-M1 (AIP-M1) connections were also selectively modulated by the observed type of grasp movement. More recently, de Beukelaar et al. (2016) looked at PMv-M1 interactions during anticipatory and actual action observation. PMv has been shown to facilitate M1 in a muscle-specific fashion while preparing and executing grasping movements (Davare et al., 2010, 2008). To investigate whether a similar facilitation via PMv-M1 pathways is observed during action observation, de Beukelaar et al. (2016) designed an experiment in which a precue (blue or white square) informative of the upcoming grasp preceded the actual grasp. PMv–M1 connectivity was modulated at the beginning of the grasp phase only, suggesting that this area is specifically involved in the encoding of online emerging visual kinematics. De Beukelaar et al. (2016) used abstract precues. It will be important for future paired-pulse TMS studies to investigate whether PMv influences the extraction of predictive information specified in visual kinematics.

In conclusion, the present study advances our understanding of the potential role of CSE during action observation. Even when the outcome

of the action is fully predictable from the initial phase of the movement, CSE follows the time course of EMG activity during the execution of the observed action. This has implication for the conceptions of the functional role of CSE, suggesting that CSE does not serve to predict the final state of the action.

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Declaration of competing interest

The authors declare no competing financial interests.

CRediT authorship contribution statement

Marco Soriano: Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Atesh Koul:** Formal analysis, Writing - original draft, Writing - review & editing. **Cristina Becchio:** Conceptualization, Writing - original draft, Writing - review & editing. **Andrea Cavallo:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107205.

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